Disk evolution

- Evolution of gas

- Evolution of dust
  - change of dust emission with age
  - transition disks

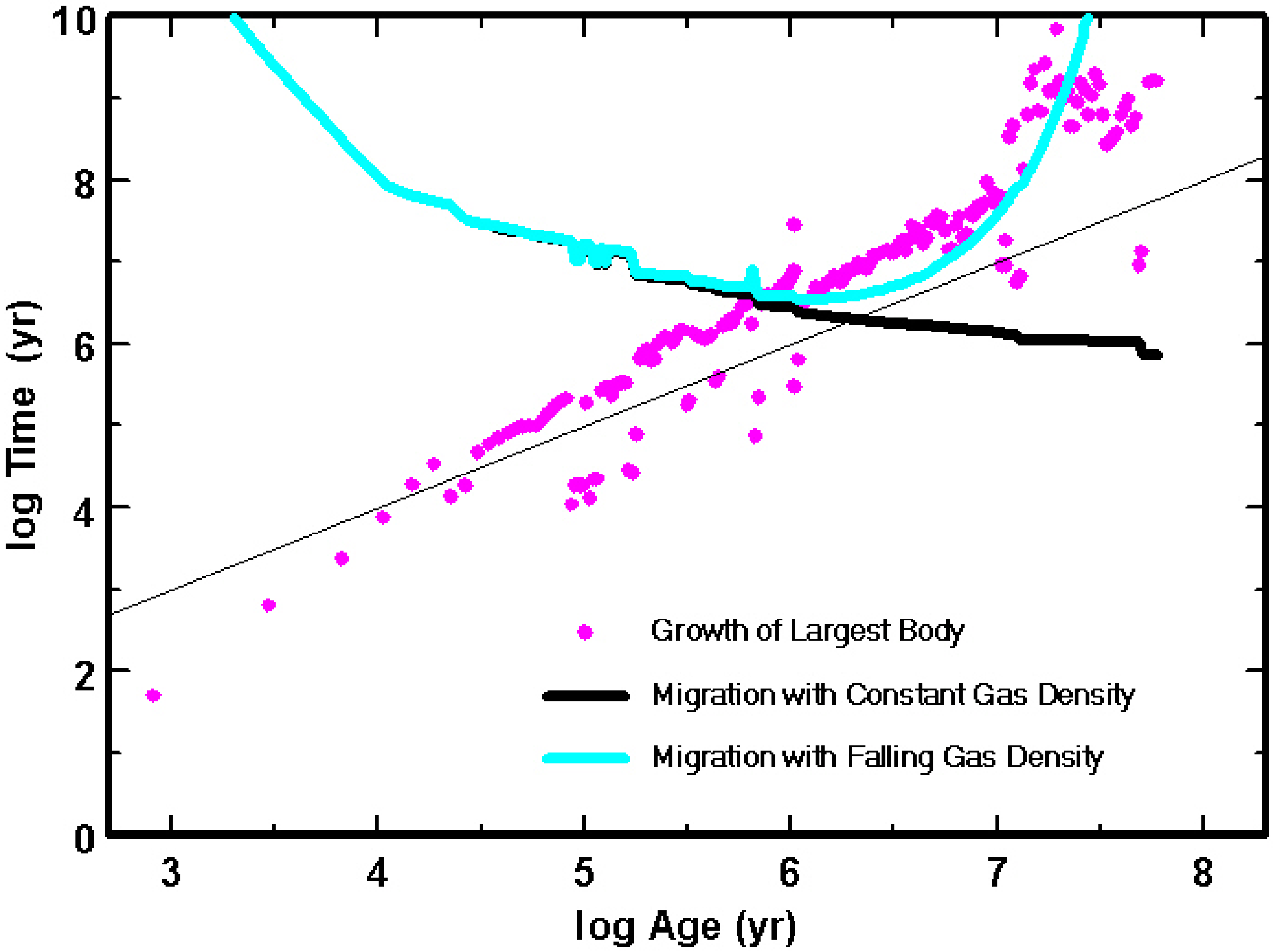
- Age as indicator of evolutionary state

Evolution of gas – disk dispersal

- Loss of gas in disk: essential for transition T Tauri disk to debris disk

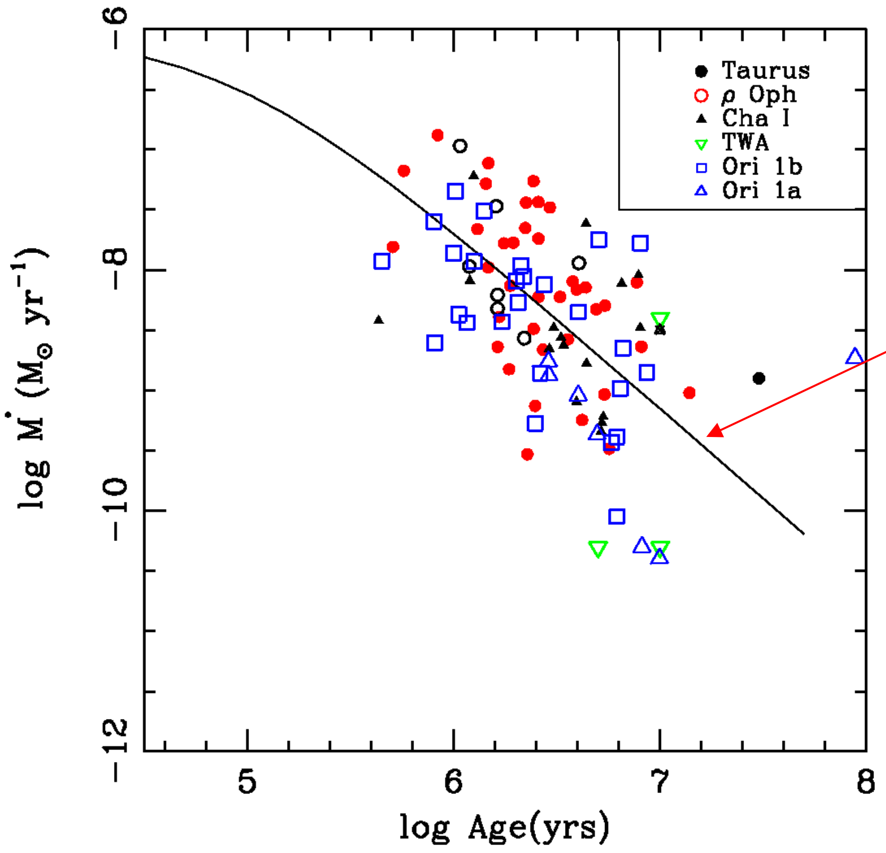
- Mass accretion rate: indicator of gas content

Migration



log Time (yr)
log Age (yr)
10
8
6
4
2
0
3
4
5
6
7
8
Growth of Largest Body
Migration with Constant Gas Density
Migration with Falling Gas Density

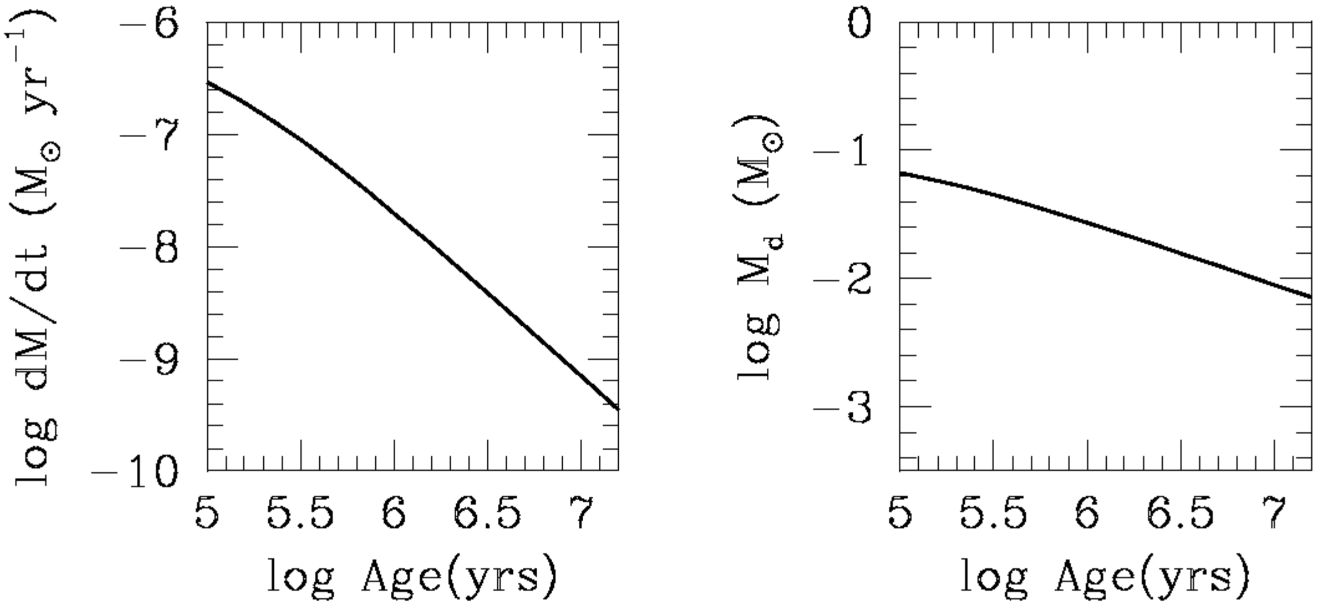
Evolution of mass accretion rate for Classical T Tauri stars (~ K5-M3)



Viscous evolution - Gas

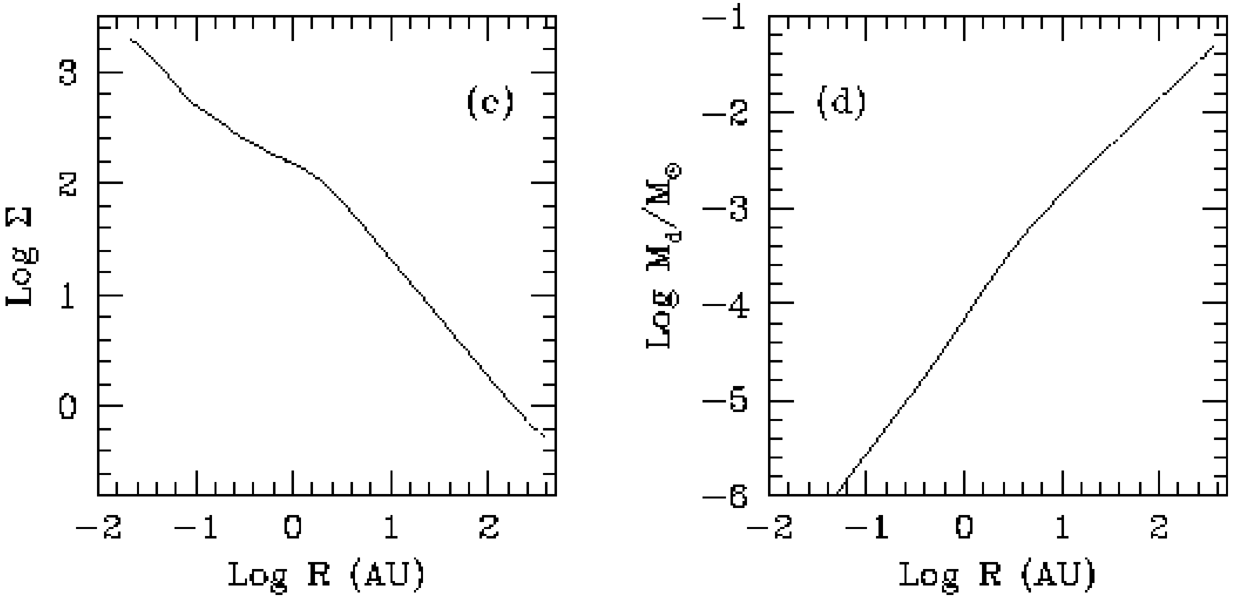
Hartmann et al. (1998), Muzerolle et al. (2001), Calvet et al. (2005)

Viscous evolution



Substantial leftover material by 10 Myr

Where is the mass?



- Most mass > 10 AU
- How does this mass dissipate?

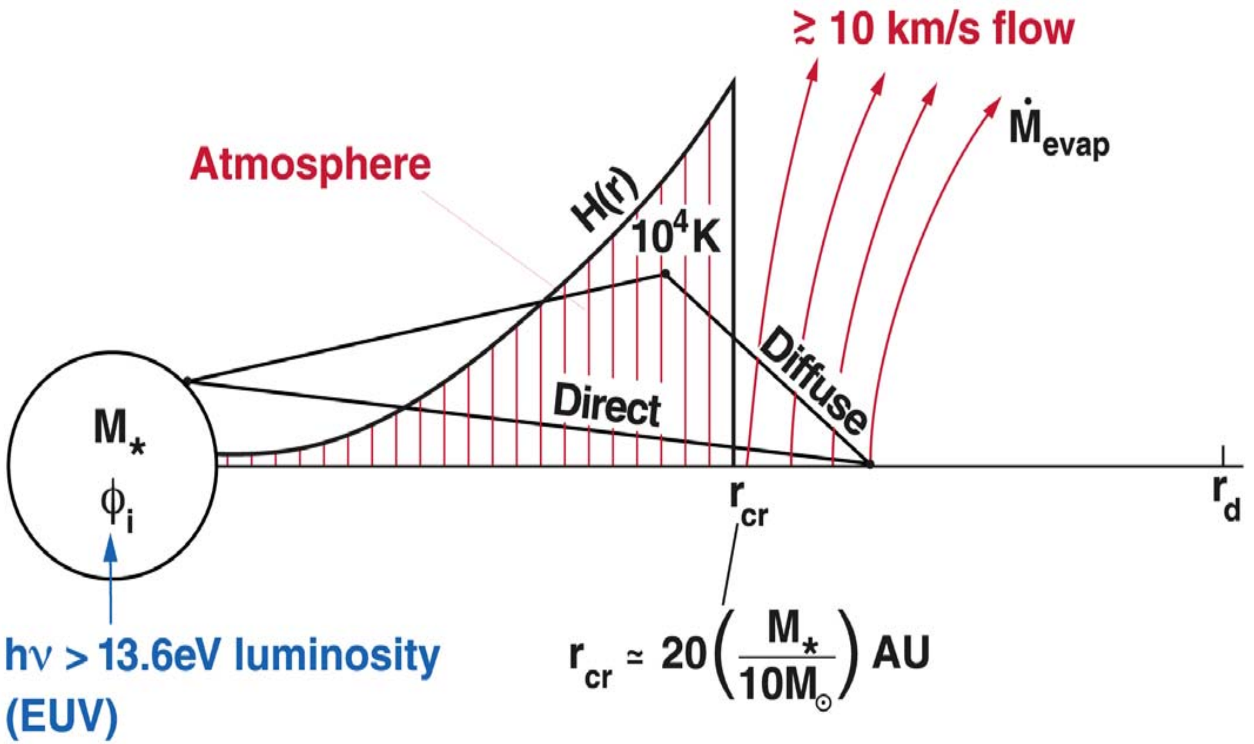
  into star / into planets / photoevaporation?

3. Photoevaporation

Slide from Uma Gorti:

<u>Central Star (EUV)</u>

Hollenbach et al. 1994, Yorke & Welz 1996, Richling & Yorke 1997

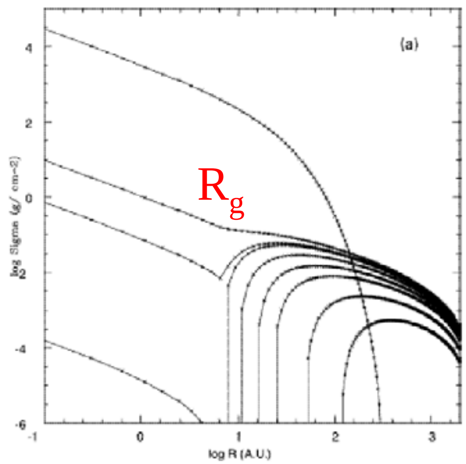


$$t_{evap} \simeq \frac{M_d}{\dot{M}_{evap}} \simeq 10^5 \left(\frac{10^{49}\ s^{-1}}{\phi_i}\right)^{1/2} \left(\frac{10M_\odot}{M_*}\right)^{1/2} \left[\frac{M_d}{1M_\odot}\right] \text{ yrs}$$

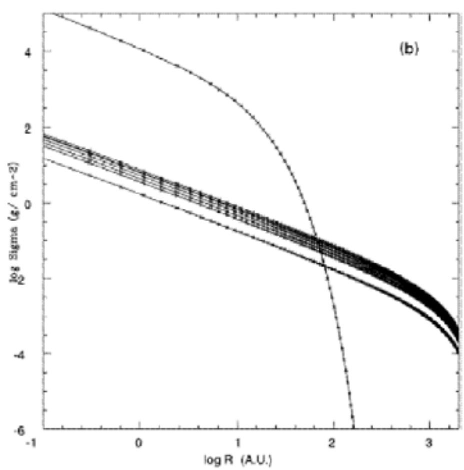
too high

Photoevaporation of outer disk?

Evolution with photoevaporation



Evolution without photoevaporation

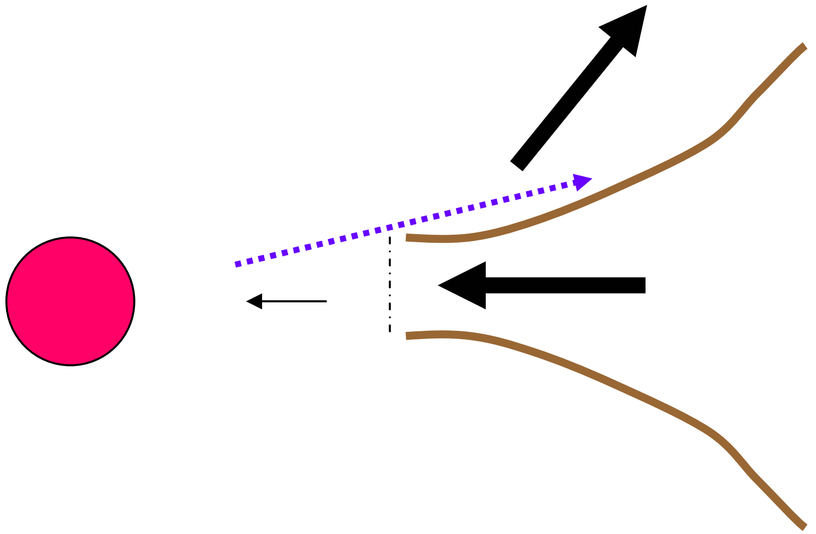


Clarke et al 2001

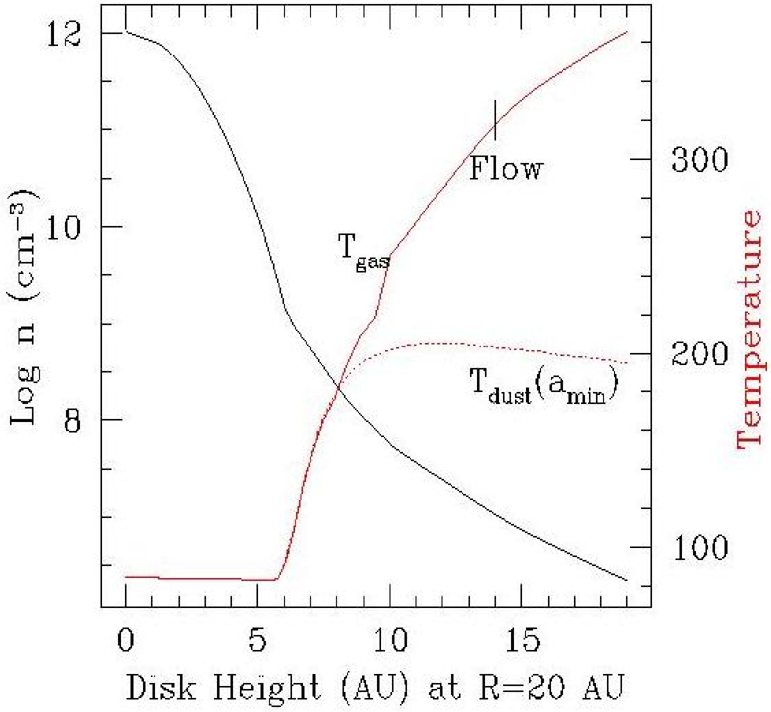
EUV radiation photoevaporates outer disk

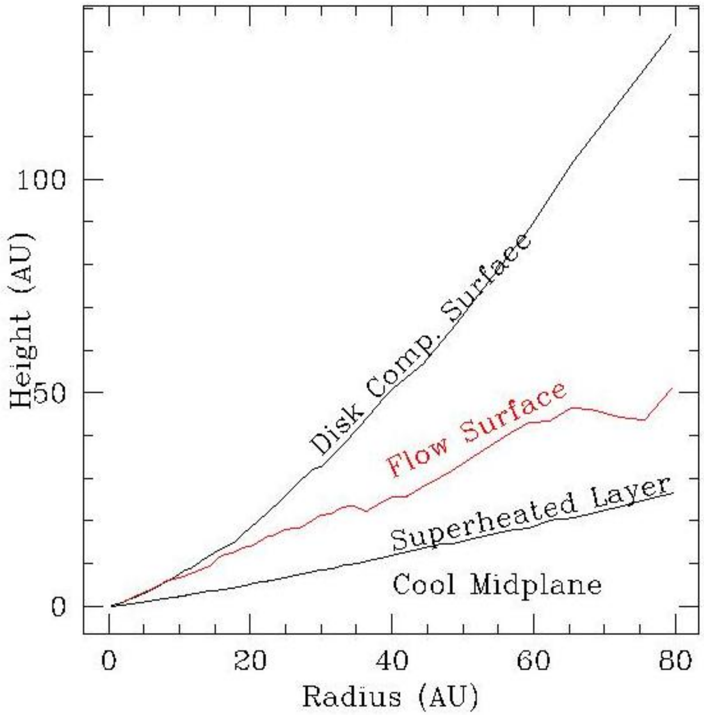
When mass accretion rate (decreasing by viscous evolution) ~ mass loss rate, no mass reaches inner disk

$R_g \sim G M_* / c_s^2(10000K) \sim 10$ AU (M_*/M_{sol})



New results by Gorti and Hollenback: Central Star (FUV and X-rays)





Heating: Grain PE heating
X-rays unimportant

Cooling: Dust Collisions
Negligible atomic/mol. cooling

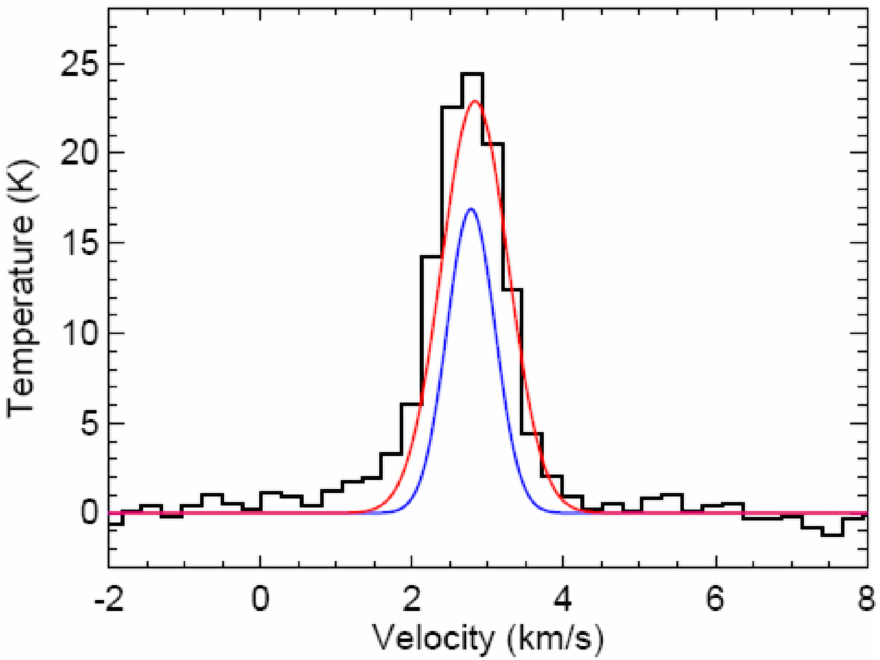
Flow originates in superheated layer of CG disk.

Uma Gorti slide

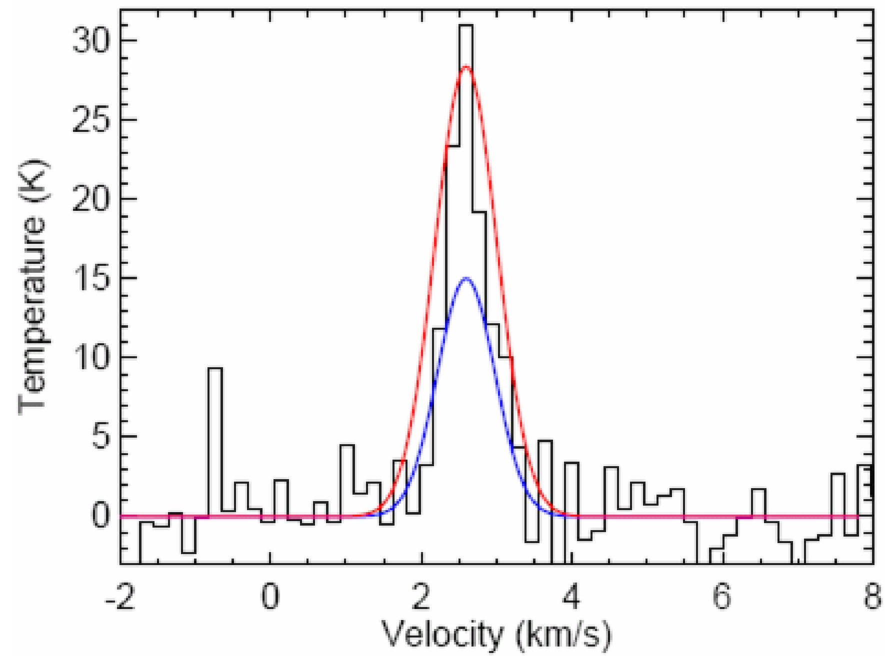
Gas dispersal

Timescales still uncertain
EUV? FUV?
Disk structures consistent with SEDs?
Constrain Tgas from molecular observations

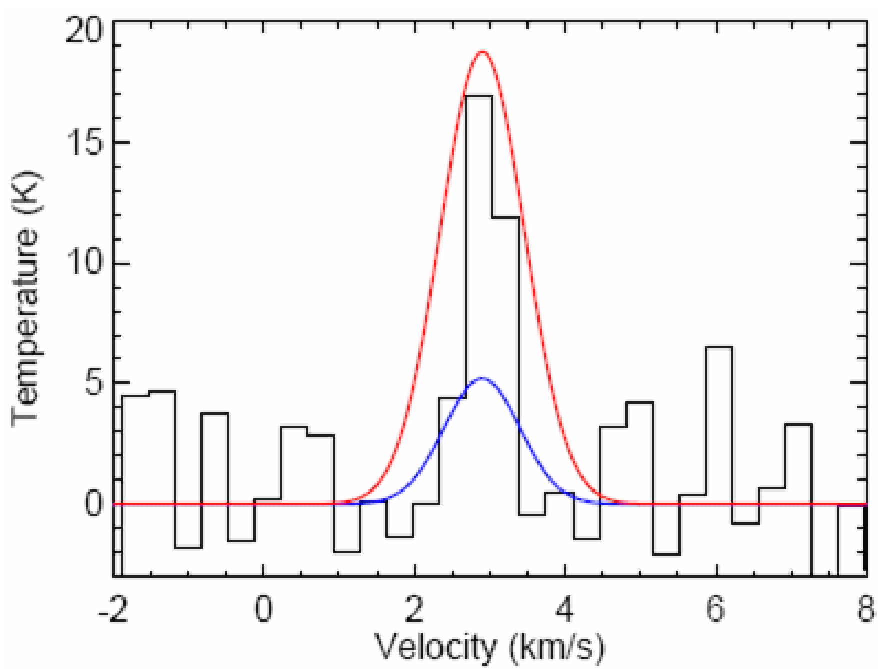
CO 2-1



CO 3-2



CO 6-5



Blue: Canonical Model (Calvet et al. 2002, Qi et al. 2004)

Black: SMA data

Red: Model with X ray heating

Slide from C. Qi

Gas dispersal

Need better knowledge of factors that induce photoevaporation of outer disks:

- FUV fluxes (HST/ACS/COS),EUV(FUSE+),X-rays
- Disk masses (mm interferometers)
- Mass accretion rates (HST/ACS/COS, optical:U, CaII-IR, near-IR:Brγ) vs age/evolutionary stage
- Penetration of high energy fluxes (models) for different dust distributions (Spitzer/models)
- Calculation of Tgas (X-rays/EUV/FUV), and photoevaporation rates (models)
- Constrain Tgas con mm molecular observations (mm interferometers)
- Chemical models, FUV

  Lyα – reconstruct from fluorescent H_2 in FUV

Dust evolution

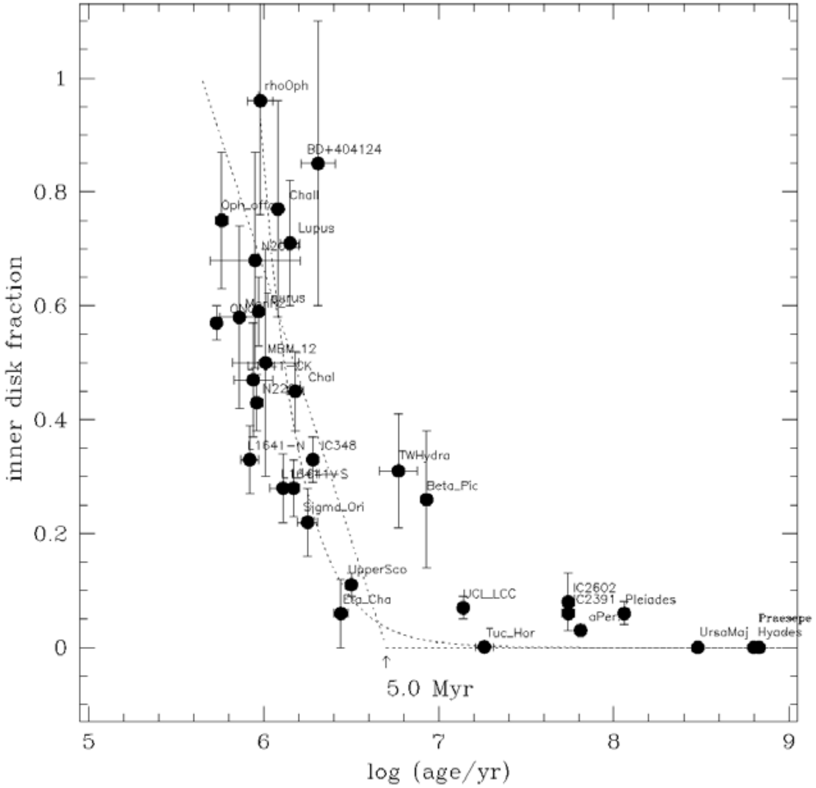
Decrease of infrared emission with age
What is it due to?
- decrease of mass accretion rate
- dust growth
- dust settling

What are the characteristic time-scales?

Dust evolution in inner disk

- Decrease of fraction of objects with near-IR emission with age
- Near-IR from inner, hotter disk

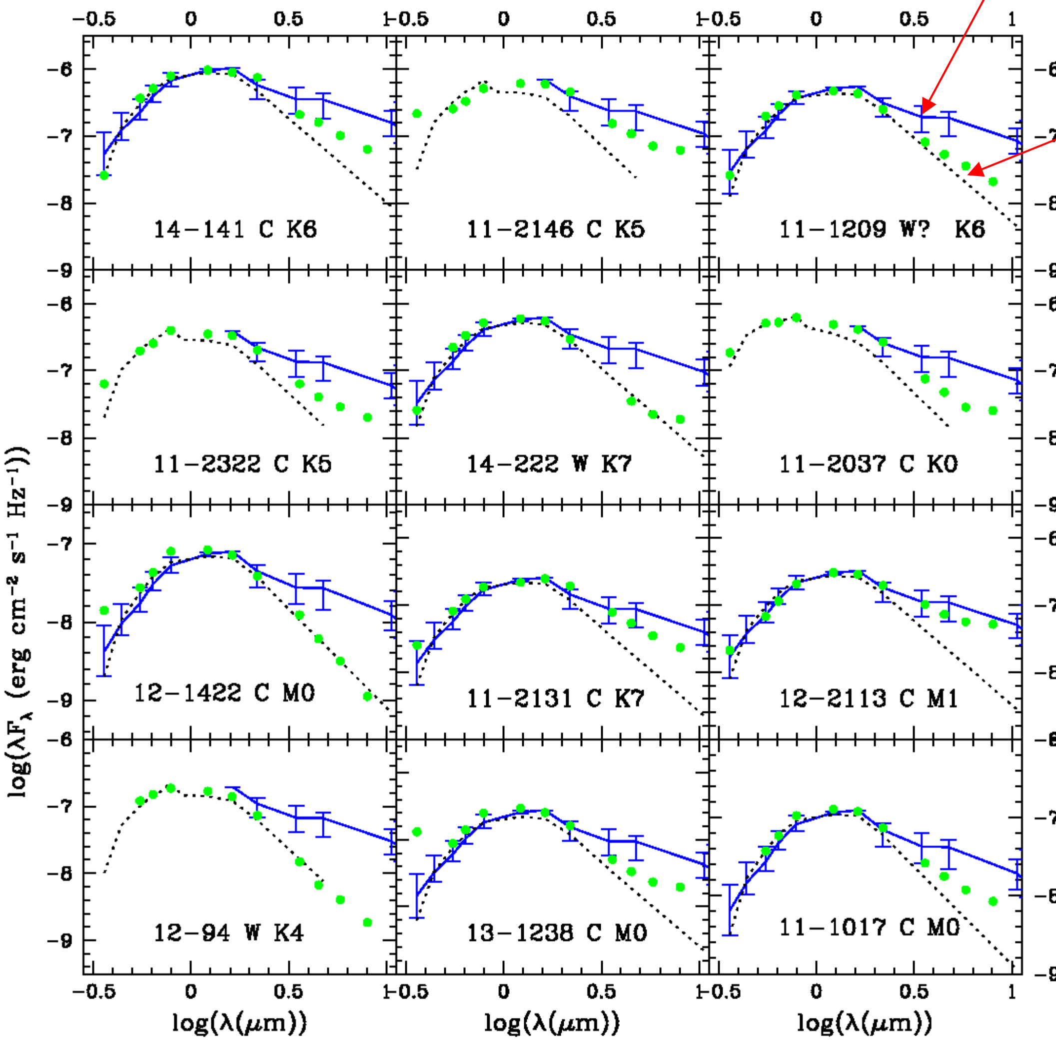
- life-time ~ 5 Myr
- large scatter



Hillenbrand, Carpenter, & Meyer 2004 (in prep)

Decrease of excess emission with age

SEDs of stars in Tr 37
~ 3 Myr
IRAC data
Weaker than median of
Taurus

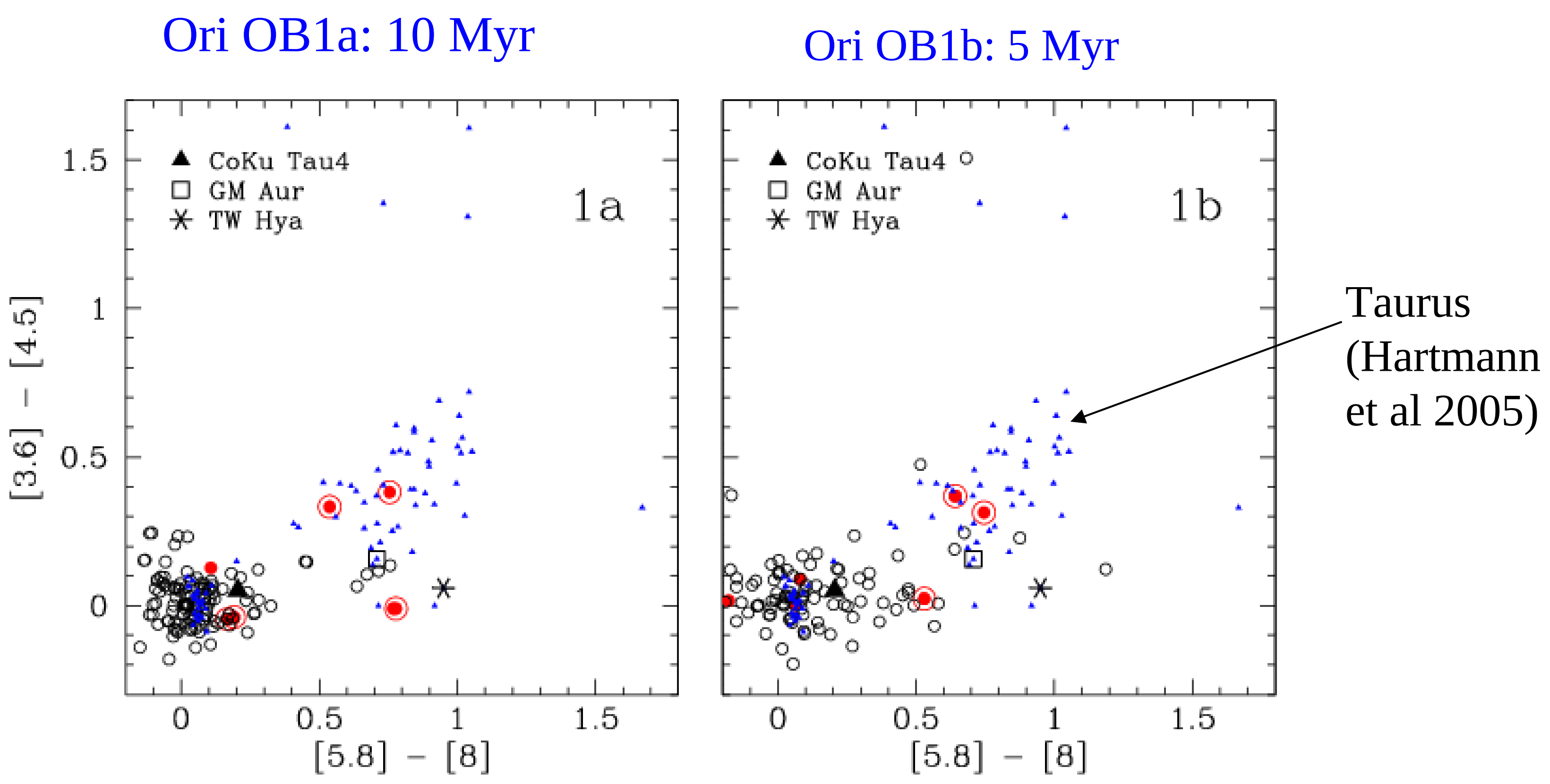


Taurus median

Phot

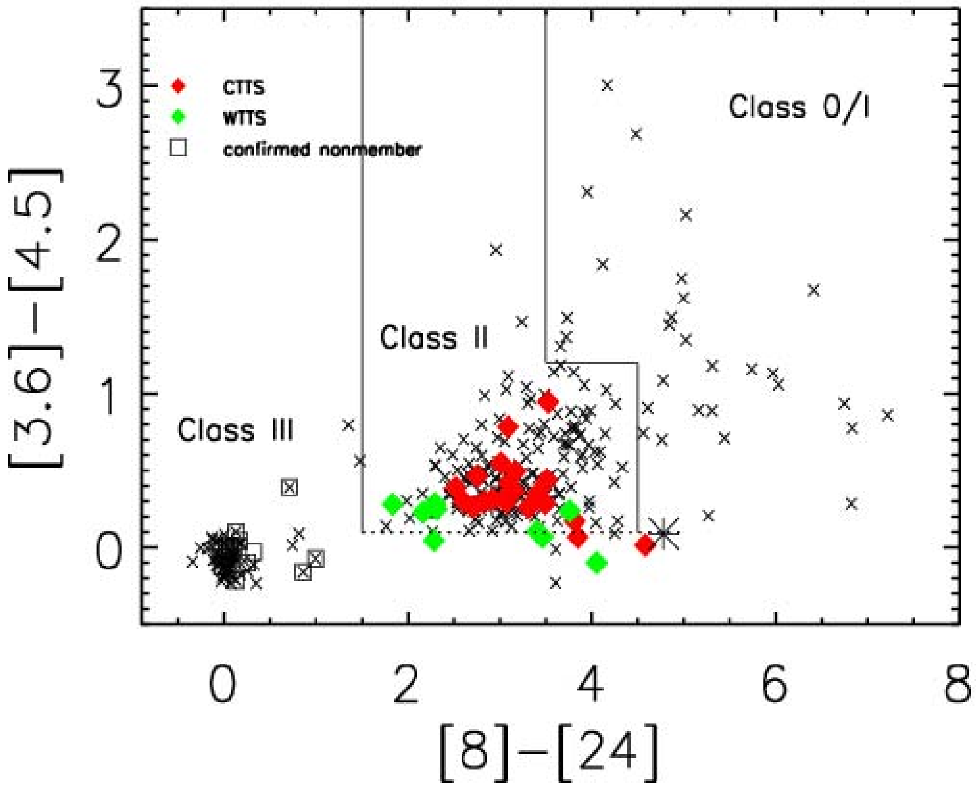
Sicilia-Aguilar et al 2005

Decrease of IR emission with age



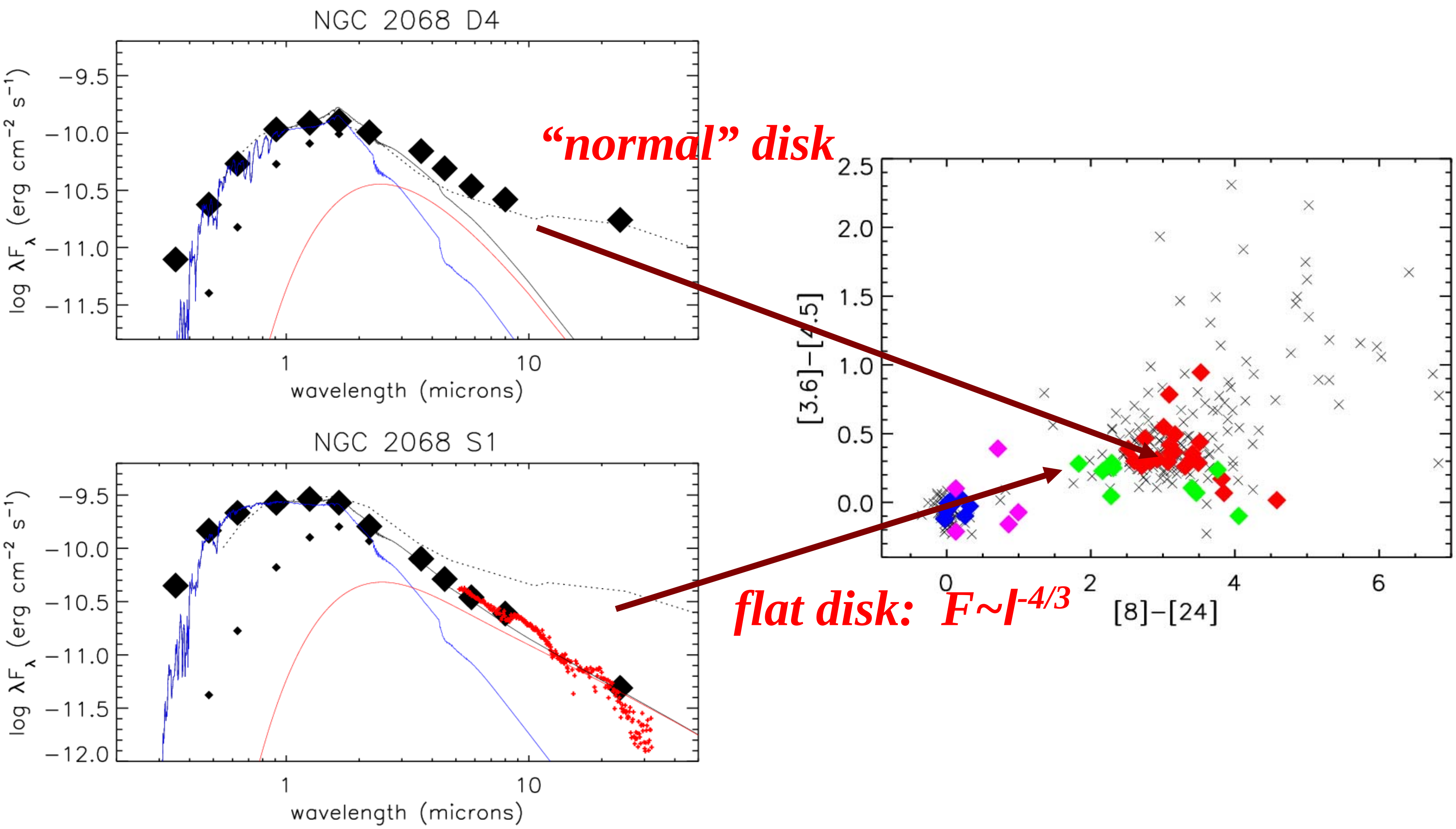
Briceno et al 2005

Range of IR emission at 1 Myr



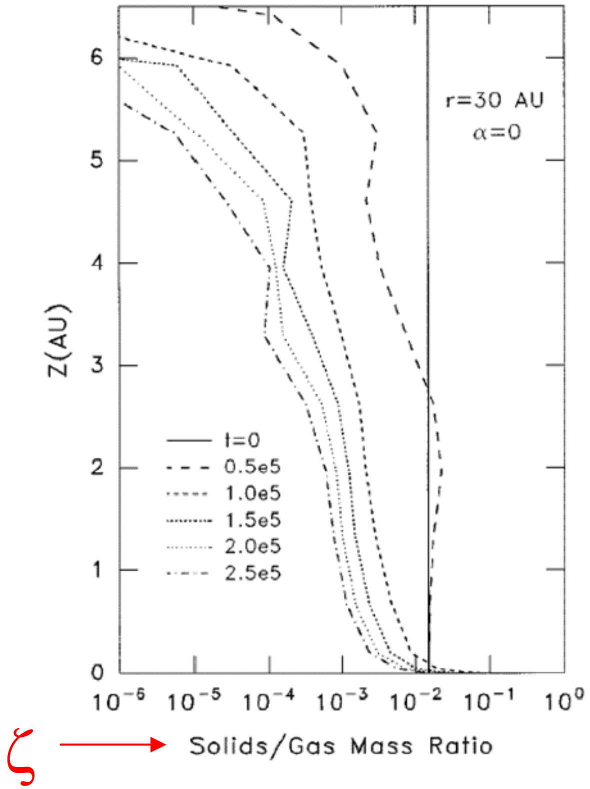
Muzerolle et al 2005

disk evolution at 1 Myr: dust settling?



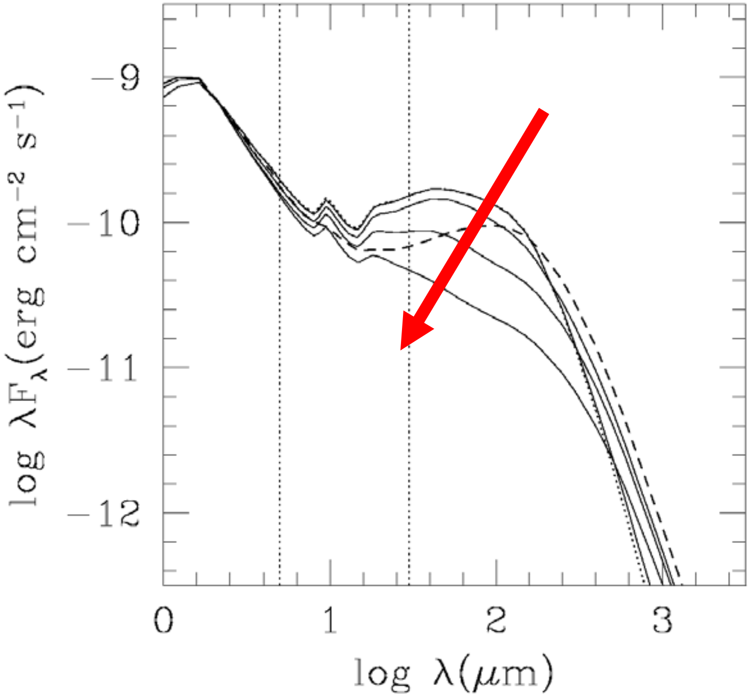
Settling – dust evolution in solar nebula

Decrease of dust/gas in upper layers



Weidenschilling 1997

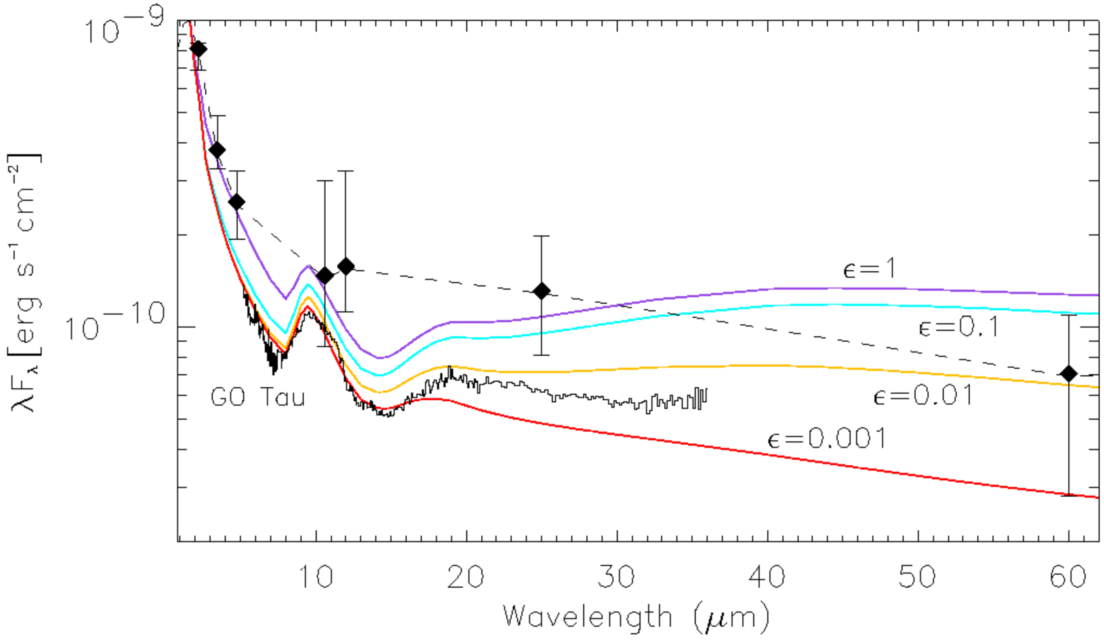
Increasing depletion of upper layers



D'Alessio et al. 2005

Settling of solids toward midplane

Depletion of upper layers: $\varepsilon = \zeta_{upp}/\zeta_{st}$



Furlan et al. 2005

Dust evolution

- Decrease of IR emission with age but spread of emission at given age
- Need SEDs of large samples of disks in populations of different ages in different environments (Spitzer: IRAC,MIPS,IRS)
- Need mass accretion rates and stellar properties for those samples (HST/optical/X-rays)
- Need models of dust evolution in disks with gas

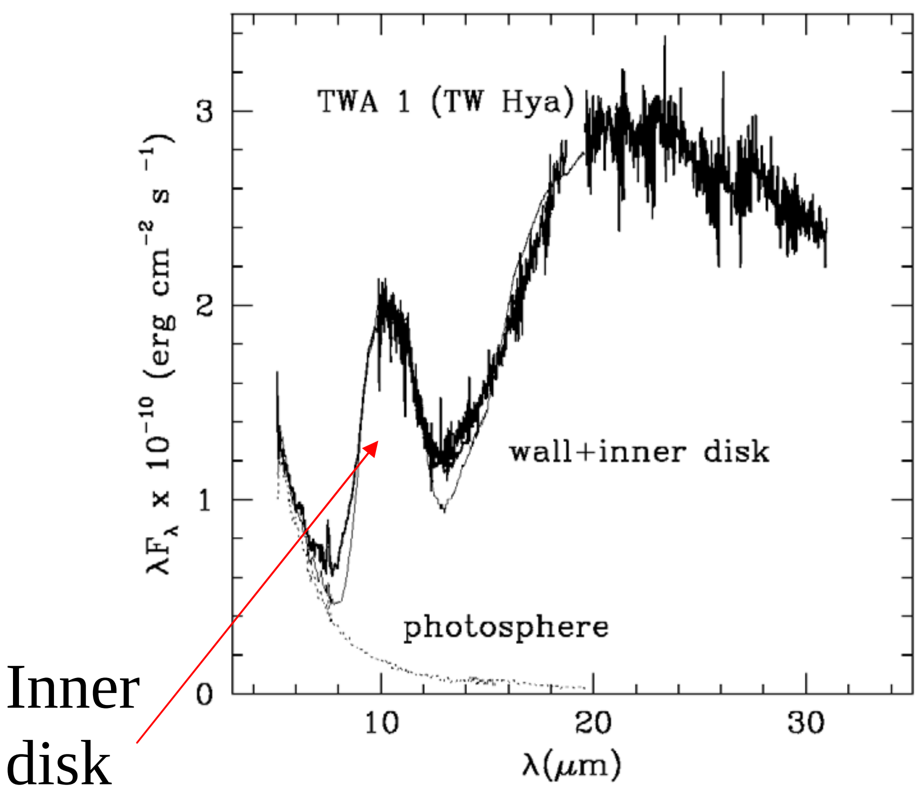
Transitional disks

- Objects with little or no emission above photosphere, but mid/far-IR/mm fluxes strong
- Interpreted as evidence of inner disk clearing
- Inner regions clear of small grains

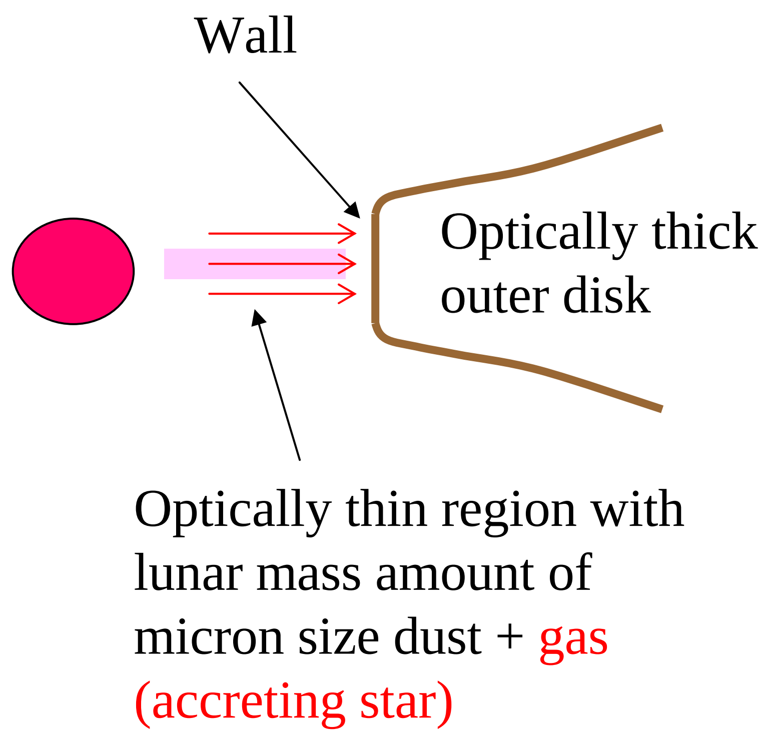
Inner disk clearing

Spectra from IRS on board SPITZER

TW Hya, ~ 4 AU
~ 10 Myr



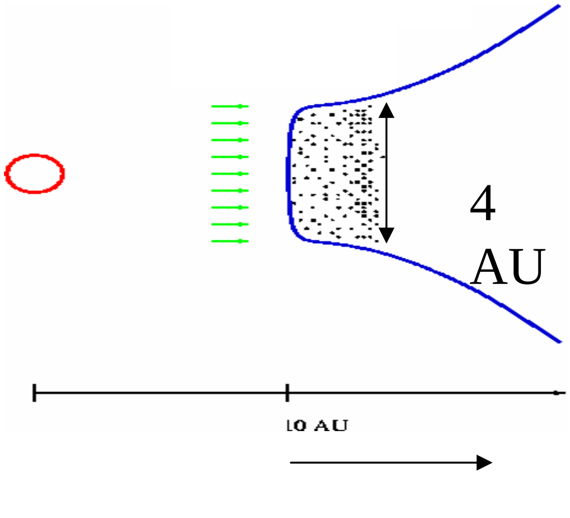
Uchida et al. 2004



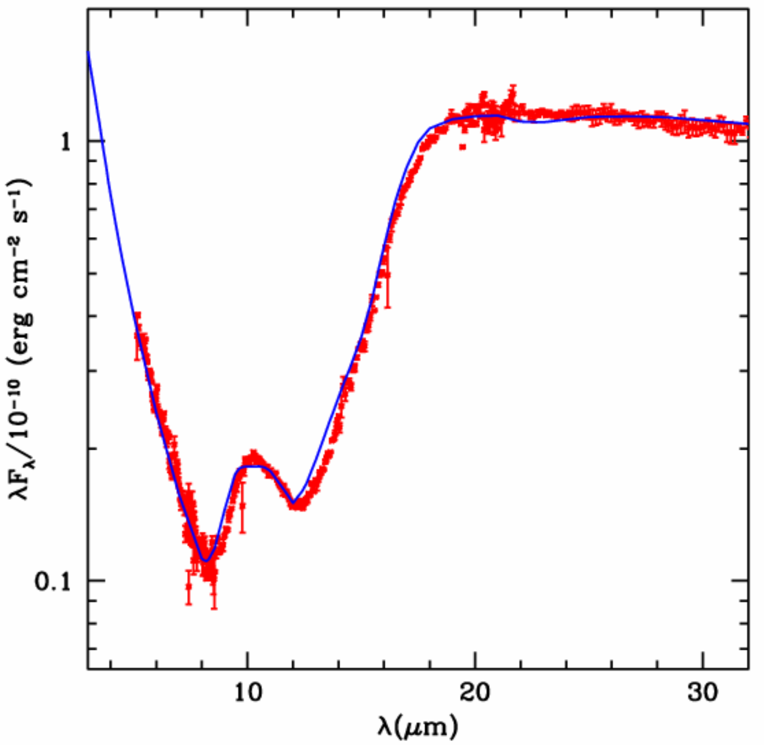
Inner disk clearing

Spectra from IRS on board Spitzer

CoKu Tau 4, ~ 10 AU
~ 2 Myr



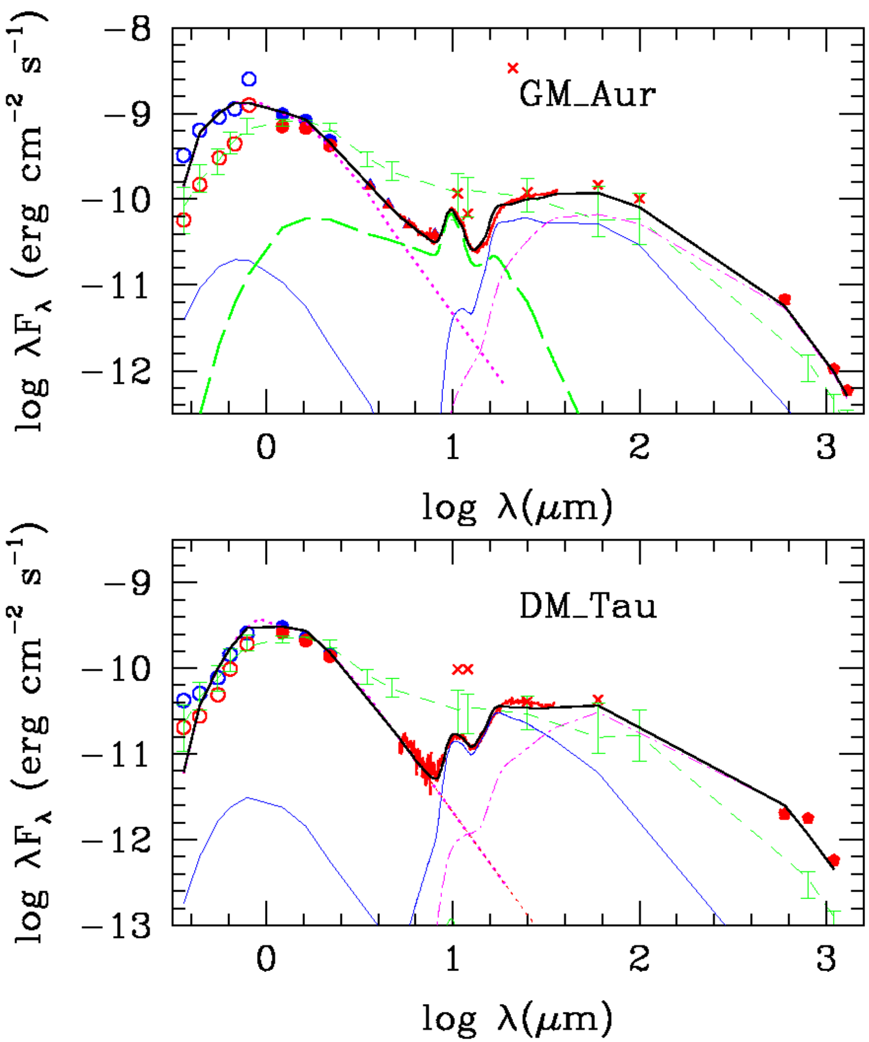
No inner disk, silicate from wall atmosphere
Non-accreting star



Forrest et al. 2004;
D'Alessio et al. 2005

More disks in transition in Taurus

IRS spectra finely maps wall region

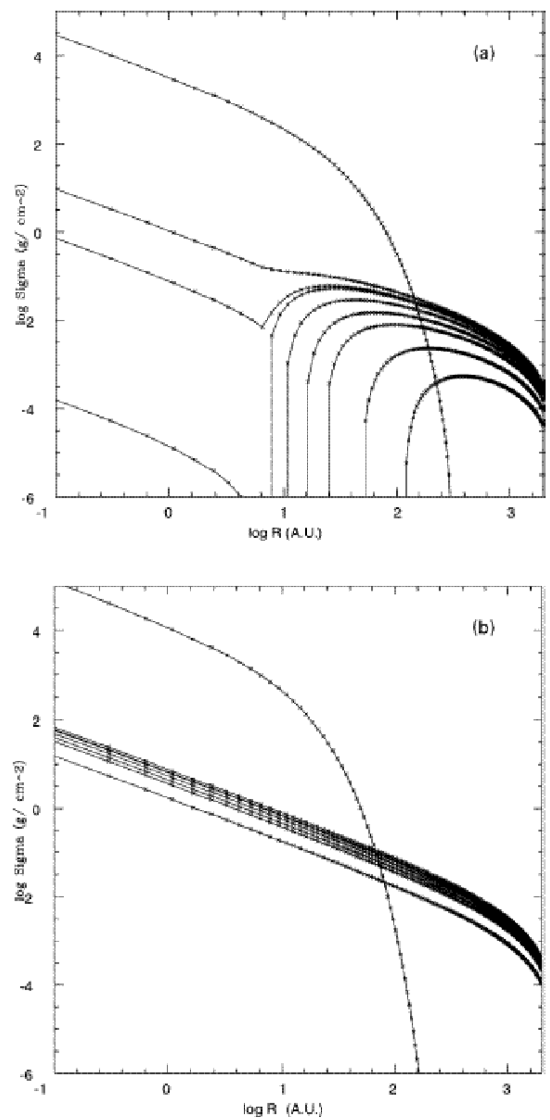


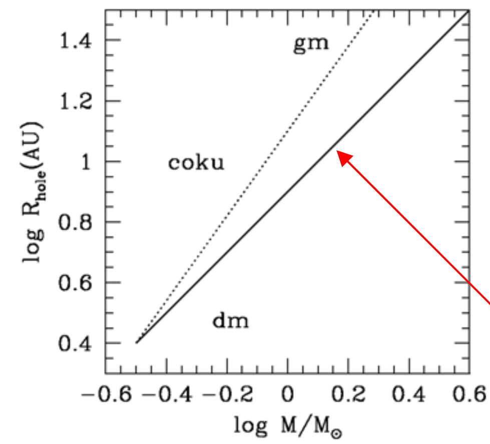
R_w ~ 24AU
outer disk +
inner disk with
little dust + gap
(~ 5-24AU)
accreting

R_w ~ 3 AU
only external
disk but
accreting star

Calvet et al 2005

Inner disk clearing: photoevaporation of outer disk?





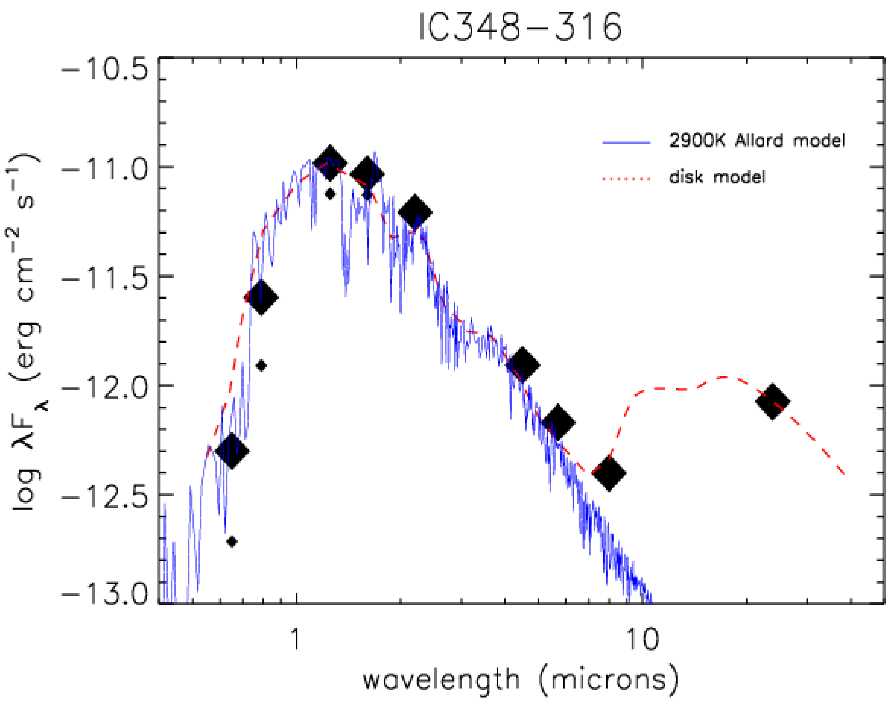
Predicted

← Evolucion without photoevaporation

Unknown EUV

Clarke et al 2001

brown dwarfs

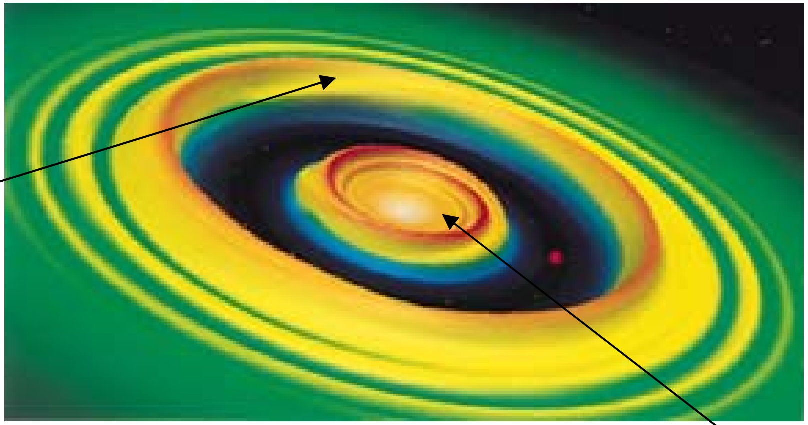


- $M \sim 0.075\ M_{sun}$
- t~1-3 Myr
- disk models require $R_{in} \sim 0.5\text{-}1$ AU
  - strong limits on formation mechanisms: no accretion; photoevaporation unlikely
  - if planet, $M \sim 2\text{-}20\ M_{earth}$

Inner disk clearing: planet(s)?

Giant planet forms in disk opening a gap

Wall of optically thick disk = outer edge of gap at a few AU



Bryden et al 1999

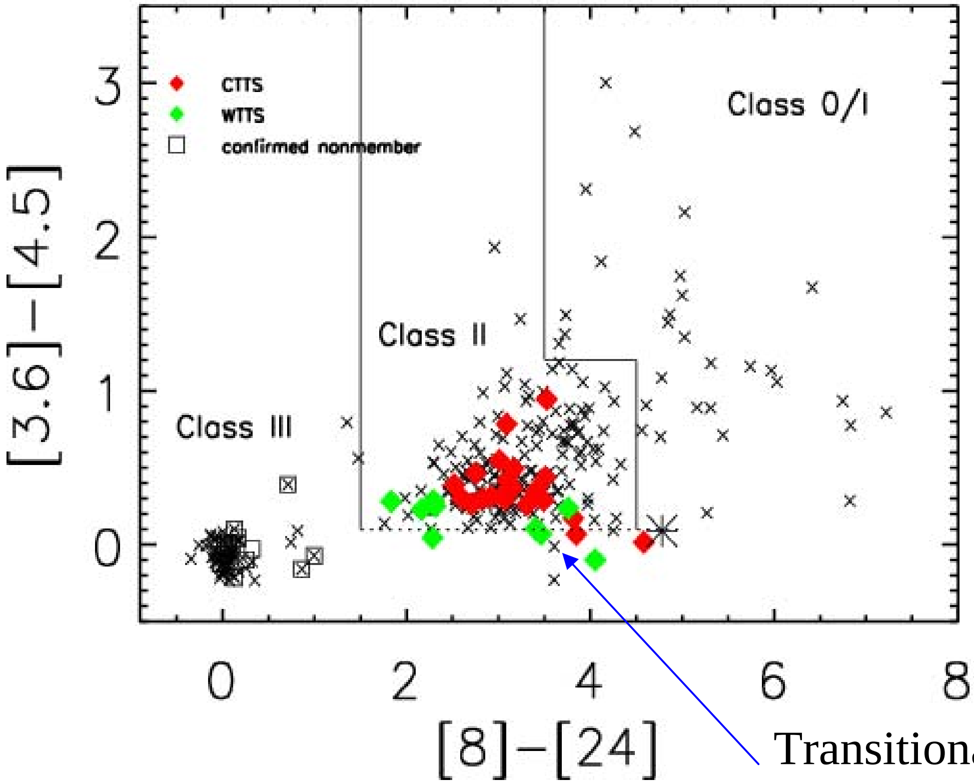
Inner gas disk with minute amount of small dust – silicate feature but little near IR excess, bigger bodies may be present

But outer disk pushes planet inwards

Inner disk clearing

Search of transitional disks in large populations: IRAC-MIPS 24 observations of clusters in a range of ages

Muzerolle et al 2005



Transitional disks

age trend?

Region	*Age (Myr)*	*Fraction of disks with holes*
NGC 1333	<1	1/66 (1%)
Ophiuchus	1	1/70 (1%)
NGC 2068/2071	1	8/174 (5%)
IC 348	1-3	10/75 (13%)
Orion OB1b	3-5	~14%
Orion OB1a	10	~6%

Transitional disks

What produces the inner disk clearing?
Does inner disk fill again? repeated episodes of disk clearing?

Need statistics of transitional disks, accreting fraction in large samples of different ages (Spitzer) to put constraints on models.
X-ray spectral observations (as in TW Hya)
Models of planet formation on gas+dust disks, timescales, migration
Models of photoevaporation

Age as indicator of evolutionary stage

Objects of very different evolutionary stage at given age of population, ie, 1 Myr old clusters with Class I's

Spread of properties at given age: dust emission (SEDs), mass accretion rate, degree of crystallinity

Age spread?

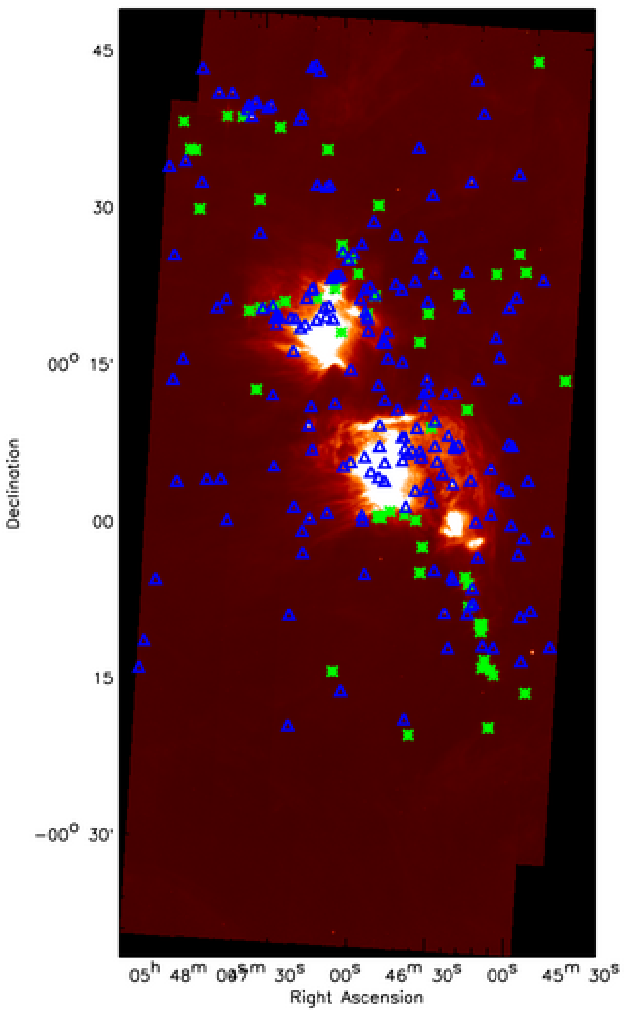
Stars born together but additional parameter(s) ?

Stochastic processes?

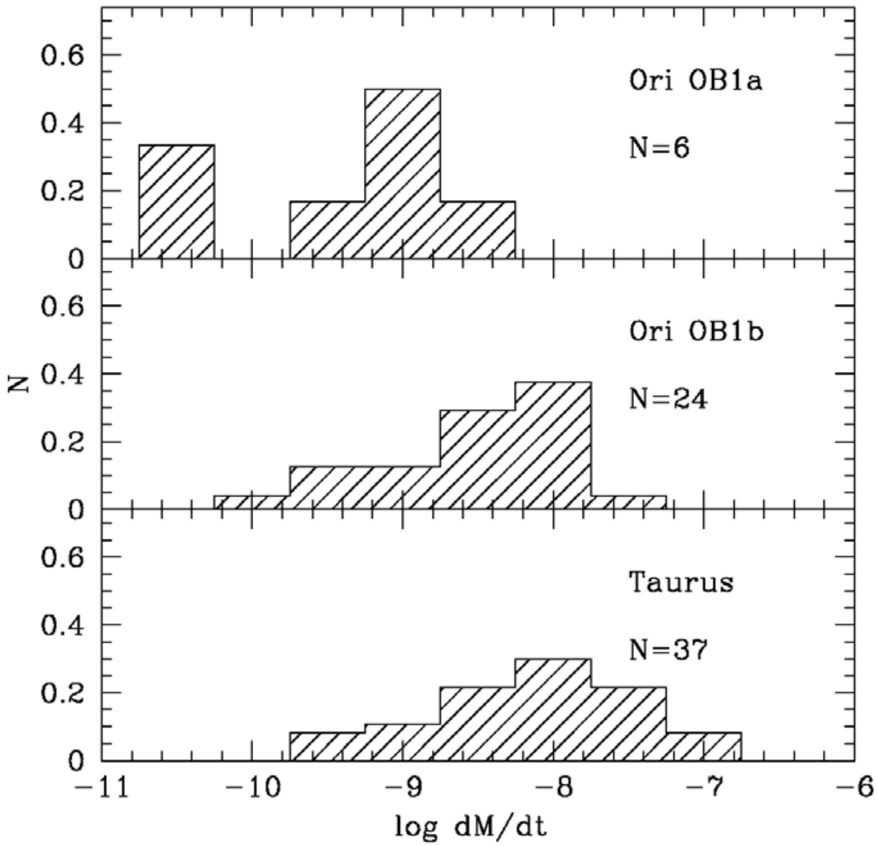
Age as indicator of evolutionary stage

1 Myr old clusters with Class I objects

Muzerolle's talk



Evolution of mass accretion rate for Classical T Tauri stars (~ K5-M3)



10 Myr

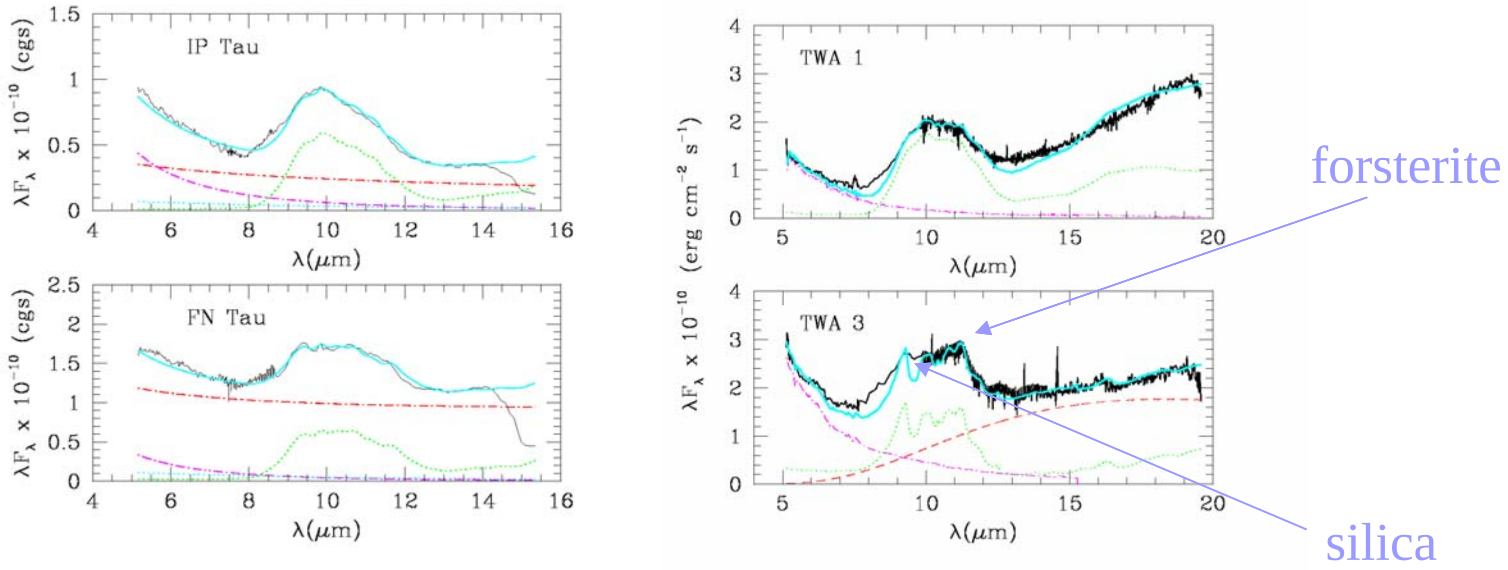
5 Myr

1-2 Myr

+ accreting objects in eta Cha and St34 (25 Myr)!

IRS data: Mineralogical content

Analysis of mineralogy of silicates: grain growth in amorphous materials, degree of crystallinity



1-2 Myr 10 Myr

Evidence for thermal processing of grains

Uchida et al. (2004); Forrest et al. (2004)

Parameters affecting evolution

Initial conditions?
Environment?
Stellar activity?

Need disk properties of samples at different ages, environments, activity indicators (L_x, degree of flaring)

Spitzer, sub/mm interferometers, Chandra/XMM

Summary

Surveys of large samples of populations with different ages, environments

- Stellar & accretion properties:
  - optical and near-IR telescopes (big and small) for M_*, dM/dt, age(s)
  - Chandra/XMM: L_x, flaring activity, spectroscopy
  - HST/COS (and UV instruments/missions needed): dM/dt, FUV, H_2, Lyα
- Disk properties:
  - Spitzer: IRAC/MIPS (characterize disks), IRS (determine dust conditions)
  - sub/mm interferometers: disk mass, midplane, chemistry, T_{gas}
  - near-IR interferometers: inner disk structure

Models: dust and gas structure and evolution, chemical equilibrium

Much progress, more to be done in preparation for extended λ coverage, high spatial resolutions of future great observatories